Space Interferometry Mission

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Abstract – The Space Interferometry Mission (SIM) flight system will be launched in June of 2005 into a nearly circular orbit around the Earth. A Delta II 7920 launch vehicle will boost the SIM flight system from the Vandenberg Air Force Base into Earth orbit. Over the next three months, the flight system will be calibrated and prepared for the science observation phase. During the science observation phase, data will be collected and returned from a precision optical interferometer on-board the spacecraft for five years and wi ll enable fundamental new discoveries in both galactic and extra-galactic astronomy.

SIM will perform unparalleled wide-angle astrometry with an angular accuracy of at least 4 microarcsecs (pas), roughly a factor of 250 over the current stale of the art, and narrow-angle astrometry with an angular accuracy of 0.6-1 µas. This precision enables the measurement of distances to sufficiently bright objects in the galaxy by direct parallax with no more than 10% error and makes possible highly accurate proper motion measurements of objects. As a consequence, SIM will allow studies of the kinematics of both isolated stars and composite systems over a large fraction of our galaxy and of large-scale transverse motions out to 100 Megaparsecs (Mpc).

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1. Introduction

The Space Interferometry Mission (SIM), originally named the Orbiting Steller Interferometer, will be NASA's first space-based science interferometer. SIM enables fundamental new discoveries in both galactic and extra-galactic astronomy by providing high-throughput 4 pas measurements of astrometric positions for objects as faint as 20th mag — 250 times more accurate than the HIPPARCOS ast rometry mission launched by the European Space Agency in August of 1989.

SIM will provide information on the size, mass distribution and the dynamics of our galaxy, will look for earth-sized planets orbiting in or near the habitable zones of 50 of the most suitable solar-type stars, wil 1 provide the frequency and orbital characteristics of giant planets and brown dwarfs orbiting nearby solar-type stars in order to learn about the formation and evolution of planetary system and the transition region between giant planets and brown dwarfs, and will provide the ages of ten globular clusters in our galaxy to an accuracy of 10' years to test models of galaxy formation and to compare with the age of the universe derived from the Hubble expansion. In addition, SIM will provide information on the dynamics and evolution of the stellar populations within our galaxy, will provide rotational parallaxes of nearby spiral galaxies, will provide information on the dynamics and evolution of binary stars, will provide luminosities for massive (O type) stars, novae, nova-like variables, planetary nebulas, and cepheid stars, ancl will provide the proper motions of active galactic nuclei, Finally, SIM will provide the proper motions and orbits of stars, spectroscopic binaries and X-ray binaries in globular clusters, will provide the masses, distances, and kinematics of massive compact halo objects (MACHOs), will provide the space-time curvature in the solar system by studying the deflection of starlight by the Sun and Jupiter, and will provide the solar grav itational acceleration towards the galactic center using high precision observations of quasar proper motions.

The SIM interferometer architecture enables imaging with a resolution of 10 milliarcsecs (mas) -- 4 times that of the Hubble Space Telescope (HST), as well as coronagraphic-type observations using starlight nulling.

SIM will image dense globular clusters with a dynamic range of 100:1 wit hin 100 mas of the cluster cores in order to measure the surface brightness at small radii from the centers. to trace the amount of mass concentrated at the centers, and to obtain proper motions of the brightest stars to estimate the central masses.

SIM, using starlight nulling, will be able to detect the brightness and spectral shapes of brown dwarf stars orbiting bright primary stars. will determine the distribution of dust in star systems with dust disks, will attempt to image a MACHO object shortly after the lensing event has ended, and will image disks of young stellar objects.

The SIM architecture also serves as a technology pathfinder for a series of future astrophysics missions, including the

Exploration of Neighboring Planetary Systems (ExNPS) mission and other NASA Origins program,

The S [M interferometer is a Iong-baseline optical interferometer operating at wavelengths in the range from 0.4 μm to 1.0 μm with capabilities for ultra-high-accuracy astrometry and high-resolut ion, high-dynamic-range imaging [1], In addition to its primary science mission, SIM, with its extensible (to longer baselines) co-phasing architecture, deployed boom, nulling beam combiner, and other technologies, serves as a technology precursor to the ExNPS infrared interferometer, SIM uses three interferometer baselines on a deployed 10 meter structure, linked by laser metrology to provide a precision structure. SIM's design draws on extensive real-world experience with ground interferometers used for astronomical observations and an ongoing technology development program to address t he specific needs of the space environment. Table 1 summarizes the SIM mission parameters.

Table 1 SIM Mission Summary

Instrument	
Baseline	10 meters
Wavelength Range	0,4 -1.0 μm
No. of Siderostats	7
Aperture Diameter	33 cm
Astrometric FOV	15 degrees circular
Imaging FOV	0,4 x 2,4 arcsec
Detector	Si-CCD & APD
Mission/FlightSystem	
Orbit	900km Sun-synchronous
Orbit Period	103 min
Launch Vehicle	Delta-[1 7920
Mass	1807 kg
Power	1912 W
Lifetime	5 years
Science Performance	
Astrometry (Global)	4 μas on 20th mag in 10 hrs
Astrometry (Narrow-angle)	1 μas on 15th mag in 3 hrs
Imaging (Point Source)	25th mag in I hr
Imaging (Extended Source)	20th mag/pixel in 1 hr
Nulling	10^{-4}
Acronyms	
milliarcsec (mas)	one thousandth Of an arcsec
microarcsec (μas)	one millionth of an arcsec
megaparsecs (mpc)	one million parsecs (pc)
parsec (pc)	3.258 Light Years (LY)
Light Year (1 .Y)	9.461 trillion km
micron (μm)	one millionth of a meter
nanometer (inn)	one billionth of a meter
picometer (pm)	one trillionth of a meter

2. Science Payload

The SIM interferometer architecture is based on a series of successful ground-bawd interferometers. Figure 1 shows a drawing of the SIM flight system which is composed of the spacecraft plus the science payload. Figure 2 shows a schematic of how SIM makes its astrometric, imaging and nulling measurements. Starlight is collected by siderostats located at ends of the interferometer and redirected to a beam combiner using a series of fold mirrors. The path difference between the two arms of the interferometer must be equal in order to produce a white-light fringe signal. A movable delay line is used to add optical path in onc arm of the interferometer. The quantity of interest for astrometry is the angle between the baseline vector and the star unit vector, θ, which is given by

$$x = B\cos(\theta) + c$$

where:

X = fringe position
c = instrument offset
B = baseline length

The fringe position gives the phase at a particular u-v point (baseline & orientation), and is measured along with the fringe fusibility which gives the amplitude information for synthesis imaging, The u-v plane is perpendicular to the line of sight to the target of interest (the u axis points North and the v axis points East). Nulling measurements arc made by adding a 180 degree phase shift to onc interferometer arm and canceling the on-axis star light.

SIM uses three collinear interferometers, by combining any six of its seven siderostats in pairs, and observes three targets simultaneously. The seventh siderostat provides redundancy for SIM. Two interferometers acquire fringes on bright guide stars to stabilize the attitude of the spacecraft in the principle angular di mensions. The attitude information is then fed forward to the third (science) interferometer which allows it to measure fringes on dim targets. Using this technique in t he absence of at mospheric dist urbances enables SIM to achieve long coherent integration times and high sensitivity.

SIM also demonstrates calibration techniques which arc scalable to longe r baselines. During observations, the science interferometer periodically calibrates itself by making observations on the two guide stars. This provides a direct measurement of the interferometer bias term. c. without moving the spacecraft. Systematic errors occurring at time scales longer than the switching time arc also calibrated out. In addition, since astrometric observations of the science targets arc made using a single interferometer, certain errors such as imperfections in the fringe detector arc common to all observations and do not affect the final astrometric measurement

SIM measures the positions of 4000 bright reference stars to establish a reference grid Targeted astrometric observations are referenced against these stars. 4π closure techniques arc used [o solve for uncalibrated instrument parameters such as plate scale (i.e., metrology laser wavelength) [2]. SIM measures the positions of the reference stars as part of its calibration procedure. These stars are measured many times over the lifetime of the mission in order to determine their proper motion and parallax.

The ability to make u-v measurements at different baselines enables SIM to image objects without a priori knowledge of their spectral properties, as well as imaging targets with narrow-line emissions. SIM performs synthesis imaging by making visibility and phase measurements at a number of u-v points. The ability to interfere any pair of the seven siderostats results in measurements with baselines between 0.5 and 10 meters in 0.5 meter increments. These measurements produce u-v measurements at varying spatial resolutions, while measurements at different orientations are obtained by rotating the spacecraft. Standard algorithms developed for ground based interferometers are used to synthesize the final image from the u-v measurements.

The SIM interferometer has three major systems: starlight, metrology, and electronics/software. The starlight system collects the stellar photons and acquires the starlight fringe patterns. Pointing and pathlength control loops are used to control the tilt and delay between the two arms of the interferometer in order to acquire the fringe signal. The metrology system is used to calibrate the interferometer by monitoring changes in the three baselines and delay line positions The electronics/software system controls the operation of the SIM interferometer and provides the control loops for the starlight system and processing for the metrology system.

SIM's use of active optics makes the in. trument insensitive to thermal deformation.s of the structure and metrology boom Alignment mirrors and articulated beam launchers are. used to direct starlight and metrology beams to their targets. The SIM instrument provides thermal control for all the subsystems. The delay line/beam combiner and electronic subsystems operate at 20 degrees C and are controlled to ± 1 degree C. The siderostat bays have similar temperature requirements. Certain components such as the siderostat mirror and metrology beam launchers have local thermal controllers which maintain their temperature stability to 10 nlilli-Kelvin (mK) for-10 minutes. First order thermal modeling has demonstrated hat this level of thermal control is feasible.

Starlight System

The SIM starlight systcrn collects the stellar photons and provides the tilt and pathlength control necessary to acquire and measure interferometer fringes. The starlight

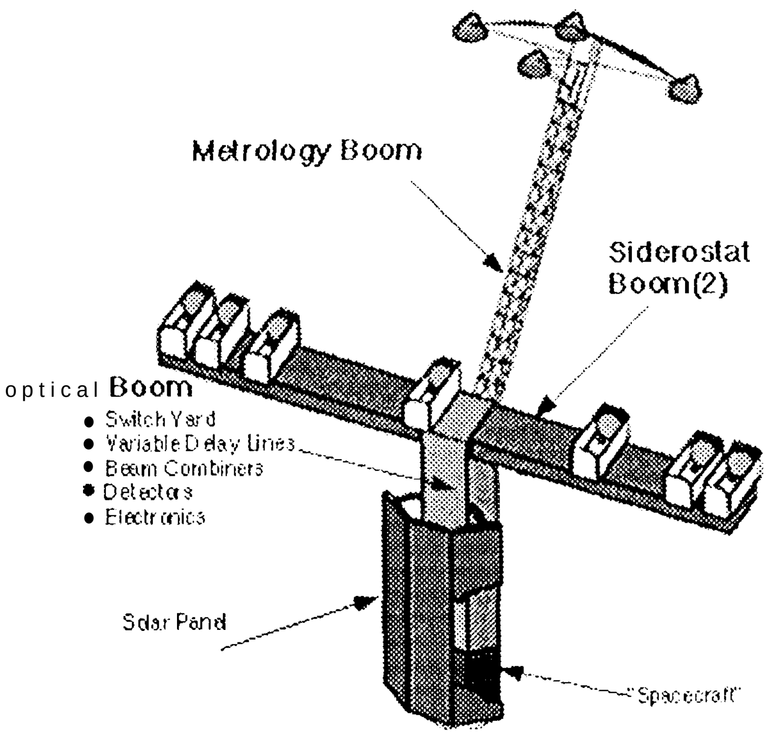


Figure 1 SIM Flight System Drawing

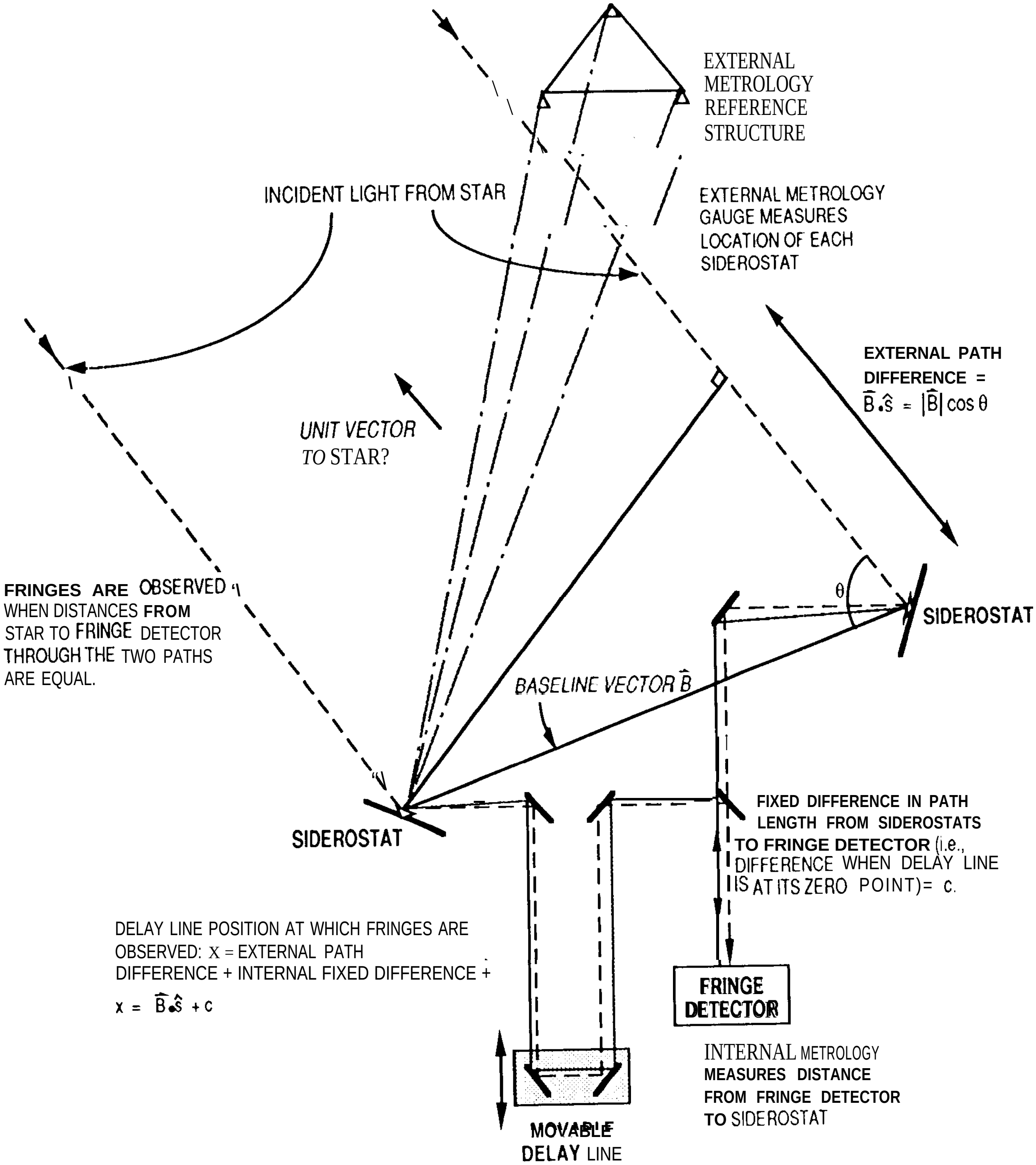


Figure 2 SIM Interferometry

system is subdivided into siderostat bays, switchyard, delay lines, and beam combiners.

The SIM starlight system has 7 siderostat bays, 6 of which are used at any one time, to form the three interferometers. Starlight is collected using a 40 cm flat mirror The starlight is then reduced using a beam compressor with a clear aperture of 33 cm and an output beam size of 3 cm. The siderostat articulates over ±2.5 degrees which allows SIM to observe a 15 degree cicular region of the sky. The starlight is then sent to a fast steering mirror (FSM) followed by an alignment mirror to direct the beam toward the remainder of the starlight optics in the central beam combining tower. Similar to ground based interferometers, the FSM and siderostat provide high and low bandwidth control of wavefront tilt, respectively. The alignment mirror provides quasi-static alignment of the starlight beam between the bays and the beam combiners. The light from the siderostat bays enters a switchyard which allows any of the bays to transmit light to any delay line/con]biner assembly. This enables SIM to make measurements with differentbaseline lengths and also provides redundancy for siderostat bays.

The SIM starlight system has five delay line/conlbiner assemblies. Three (plus 1 spare) are used for astrometric and imaging measurements and the fifth is used for nulling interferometry. Each assembly uses one active and one fixed delay line. The active delay line has an accuracy of 1 nanometer (rim) and a range of 1 meter as needed to observe stars within the 15 degree circular region of sky. The SIM active delay line design is based on a long history of ground based designs and uses a cat's eye configuration with three levels of control: a motor for the long throw, a voice coil 10 isolate the optics from the motor and a Piezo actuator (PZT) for high bandwidth control, The fixed delay line is simply an active one with no actuators. It is used to maintain the polarization properties between the two arms of the interferometer. The beam Combiner interferes the light from two arms of the interferometer and detects the stellar fringes. Additionally, the beam combiner detects wavefront tilt for both interferometer arms. The fringe pattern is detected using both a dispersed fringe spectrometer, which has a large capture range, and an avalanche photo diode (APD) for high sensitivity operation. The dispersed fringe spectrometer uses a slit to increase SIM's instantaneous field of view to 0.4 x 2.4 arcsecs. A single charge coupled devise (CCD) detector is used for both the dispersed fringe detector and the tilt sensor. The SIM fringe tracker can use current tolv-noise CCD technology to meet its requirements. However, newer devices which will evolve from the technology program, such as a 128 x 128 backside illuminated device using skipper (multiple nondestructive reads) technology producing low read noise at high readout rates (100 Hz frame rate), will be incorporated if they become available. The beam launcher for the internal metrology gauge uses a design similar to the external metrology launchers, described in the next section, and is shown as part of the beam combiner.

A nulling beam] combiner uses an achromatic nulling interferometer design similar to that proposed for the ExNPS interferometer to produce a high level of starlight cancellation for an on-axis star. The beam combiner interferes light from two arms of the interferometer and produces cancellation by introducing a 180 degree phase shift in one of the arms. Achromaticity is achieved by implementing the phase shift with a polarization flip as opposed to a path delay. The nulling subsystem uses the delay line to accurately control the pathlength between the two arms. Single mode fibers eliminate the effects of wavefront aberrations. Steering mirrors match the amplitude between the two arms by modulating the amount of light coupled into the fibers.

Metrology System

The S1 M metrology system monitors the systematic errors at the 10 picometer (pm) level to achieve the 4 pas astrometric performance. The metrology system is composed of the internal metrology subsystem and the external metrology subsystem. The internal metrology subsystem monitors the path difference between the two arms of the interferometer thereby measuring the position of the stellar white light fringe.

The internal metrology beam launcher is integrated with the beam combiner and uses the inner 5 mm of the optical aperture. The internal metrology system, based on the Palomar Testbed Interferometer design, launches a metrology beam which is concentric and parallel to the starlight beam and measures the distance from the beamsplitter to the corner cubes on the siderostat.

The external metrology subsystem measures changes in the baselines oft he t hree interferometers. An external metrology beam launcher assembly is located at each of the vertices of the metrology reference tetrahedron The beam launcher assembly interrogates each of the siderostat corner cubes. Since only three launcher assemblies are needed for triangulation, the fourth set of launchers is redundant and provides a consistency check on the metrology data. Each set of launchers shares a common optical fiducial, a dual hemisphere cat's eye Six additional metrology beam monitor the distances between the cat's eyes and hence the vertices of the reference structure. In this manner, a deterministic optical truss between the reference structure and the siderostat mirrors is formed. Both the internal and external metrology subsystems use the same corner cubes located on the surface of the siderostat mirrors

The SIM metrology system uses heterodyne laser gauges similar in principle to those in commercial systems to nlca.sure distances between optical fiducials Two types of laser gauges are used relative gauges which measure distance changes at the 10 pm level, and absolute gauges which are used to calibrate the dimensions of the optical truss at the 10 micron (pm) level Both laser gauges use a Neodymium Yttrium Aluminum Garnet (Nd:YAG) laser at

1.3 μm, which is not visible to the science detectors on the beam combiners. SIM uses the same laser for all of its metrology gauges, and since both the baseline and fringe position are measured with the same "ruler", changes in the laser wavelength do not affect the measured astrometric angle.

Electronics and Software System

The Electronics and Software System includes the flight instrument computer, the drivers for the Opto-mechanical components, and the detector electronics for the fringe trackers and metrology sensors. The SIM instrument uses three advanced flight computers to control the instrument and acquire the fringe and metrology data. The SIM instrument produces 6.7 Gbits of data per day, which is compressed and stored along with the engineering data in the spacecraft computer prior to down link.

SIM takes advantage of the extensive software development effort undertaken as part of the ground-based and testbed activities, utilizing algorithms and software modules for the interferometer light software. SIM and these ground based interferometers share a common software architecture. This helps to address the issue of software complexity, an area that has always been a major issue in the integration and test of interferometers.

Astrometric Science

The astrometric science objectives of SIM are summarized in Table 2. SIM performs unparalleled wide-angle astrometry, with an accuracy of *at least* 4 μas, roughly a factor of 250 over the current state of the art (*i.e.* the HIPPARCOS mission). For narrow-angle applications (dark companion detection) SIM will perform narrow-angle astrometry of 0.6- I pas. Astrometric measurements of this precision enable the measurement of distances to sufficiently bright objects in our galaxy by direct parallax with no more than 100/0 error. Astrometry at this precision makes possible highly accurate proper motion measurements. These two capabilities taken together give SIM the ability to probe kinematics of both isolated stars and composite systems over a large fraction of our galaxy. and probe large-scale transverse motions out to 100 Mpc.

SIM makes astrometric measurements by using six of its seven siderostats to form three independent interferometer baselines. Two baselines are used to observe bright guide stars from the reference grid. The information from these two interferometers is used to control spacecraft attitude and instrument configuration for the third baseline as it observes the potentially-fainter science target. *A posteriori*, individual measurements on a given science target are combined with global reference grid information to derive the target position estimate [2].

The analysis here uses conservative estimates for SIM's 1σ performance: a wide-angle astrometric accuracy of 4 μas, and a narrow-angle astrometric accuracy of 0.6– 1 μas. Taking single measurements at the beginning and end of the five year mission yields a proper motion precision of 1.6 pas yr^{-1}. Systematic errors in the astrometric measurements are present at some level although it is difficult to estimate what fraction of the error is systematic at this point. For planning purposes the systematic noise floor for multiple measurements is assumed to be one half the quoted values.

Table 2 Astrometric Science Summary

Science Topic	Objective	Target Description	Magnitude Range	Comments
Dark Companions	Astrometric Detections of Planets, BD, WD, MACHO Candidates*	Nearby Stars, LMC, Silt, and Bulge Field Stars, Possible MACHO Companions	5- 22	Detect Gas Giants; BD and WD companions, MACHO Astrometric Effects
Luminosity Calibration	Calibrate/Constrain Astrophysical Models	MS Stars, Cepheids, RR Lyrae, PN, Nova/CV	4 20	Calibrate Standard Candles (O(1%) range error)
Binary Systems	Mass Distributions of Binary Constituents	MS Binaries, CV (White Dwarfs), XRB (Neutron Star.. Black Holes)	12 20	Unequivocal Mass Distributions
Globular Clusters	Calibrate Cluster Distances/Ages, Cluster Dynamics	Globular Clusters (47 Tuc, to Cen, M15, etc)	12- 20	Cluster Age Determination, Dynamics (Crowded Field Operation)
Galactic Structure	Rotation Curve Spiral Arm Halo Kinematics	Early Main Sequence@ 2 20 kpc, Halo K Giants	10 20	Spiral Arm Densities, Dark Matter Distribution
AGN	BLR Fluctuations. Transverse Peculiar Velocities, AGN Microlensing	AGN Within 100 Mpc	13 20	Correlate Astrometric and Photometric Fluctuations, Large-scale Densities

• Aconyms are defined in Table 3.

although the theoretical capability of the SIM instrument is much higher duc to its 10-m baseline. For instance, performanceof the 3-dimensional metrology system at the 10 pm level reduces the astrometric error to 0.2 µas.

Imaging Science

The imaging science objectives of SIM arc summarized in Table 3. SIM performs synthesis imaging at a resolution of 10 mas over a 400 mas field, The u-v plane is sampled by rotating the baseline around the line-of-sight to the target, and by making visibility measurements using differentpairs of siderostats. As in astrometric mode, two interferometer baselines track guide stars to maintain attitude and pathlength control for the third interferometer. This third interferometer collects science data by imaging (he dispersed wide-band fringe along one axis of a CCD detector, measuring visibility amplitude and phase. This capability allows SIM to perform multispectral imaging at $\delta\lambda/\lambda \sim 1\%$. The second axis of the CCD is used to image multiple subaperture acceptance regions concurrently, so the effectivesize of a combined synthesized image is 0.4 x 2.4 arcsecs.

Particularly interesting for the ExNPS mission, SIM will inchtdc a nulling beam combiner for usc in image synthesis. Nulling opens a large number of possibilities for imaging experiments where a bright object's light would otherwise make the detection of a faint companion and/or underlying structure impossible. This nulling technology is at the heart of the long-baseline ExNPS interferometer, and its demonstration by SIM will bc an important demonstration of the technique's viability.

The combination of SIM's astrometric and imaging capabil it ies make it a powerful inst rument 10 study a broad range of astrophysical problems, from astrometric surveys of nearby stars to the cosmic distance scale and mass distribution

3. Spacecraft

The spacecraft is composed of engineering subsystems designed to bc robust, minimizing both development risk and flight risk.

Only technology expected to be demonstrated by required commitment dates is used. This balances the benefits of new technology versus the risk of development, Acceptable "off the shelf' backups have been identified in all cases where new technology is not currently available. The spacecraft utilizes class–S parts with block redundancy for critical engineering functions. No life limiting consumables arc used. The spacecraft is designed radiation hard to >100 krads. Where parts are not available to meet this requirement, analysis and shielding will bc used to insure adequate radiation margin. Large margins for mass, power, and data handling arc provided to enhance acceptable cost and schedule risks.

The major requirements driving the design of the spacecraft (S/C) are shown in Table 4.

Table 3 SIM imaging Sciencc Summary

Target Classification	Objective	Typical Soured Surface Brightness	Total Int Time
Brown Dwarf (GL229B prototype)	Survey Physical Parameters	14 - 18 mag	6 hrs
Globular Clusters	Core Resolution, Dynamics	8 - 14 mag	6 - 24111>
Main Sequence (β Pic prototype)	Superplanets, Exo-Zodical F.mission	12 I 5 mag asec^{-2}	24 36 hrs
YSO Disks (GM Auriga prototype)	Resolve Disk Densities and Fe atures	12 mag asec^{-2}	24 30 hrs
AGN NLR (NGC 2110 prototype)	Resolve NLR Emission [.ine Features	O(10^{1}) photons m^{-2} s^{-1} asec^{-2}	24 30 hrs
Distant Galaxies (HDF Example)	Early Galaxy Morphology	16 18 mag asec^{-2}	24 96 hrs

Acronyms:
AGN Active galactic nucleus, BD Brown dwarf, BLR Broad line region, CV Cataclysmic variable, HDF Hubble deep space, LMC Large magellanic cloud, MACH[0 Massive compact halo object, MS Main sequence, NGC New general catalogue, NLR Narrow line region, PN Planetary nebula, SMC Small magellanic cloud, WD White dwarf, XRB X-ray binary, YSO Young stellar object

Table 4 Spacecraft Requirements

Mission life	5 years, minimum
Trajectory	Earth Orbit, Sun Sync
Orbital Altitude	900 km circular
orbital Inclination	99°
Orbital Period	103 minutes
Trajectory Correction Maneuvers	none
Sun Occultation	none for ~ 250 days/year, 0.3 hours max during < 100 days/year
Orbital Velocity Determination	4 mm/sec
Pointing	
Spacecraft Turn	90 degrees in 5 min
Spacecraft Attitude Control	15 arcsec
Spacecraft Attitude Knowledge (after ground processing)	5 arcsec
Spacecraft Attitude Stability	6 arcsec/sec
Thermal and structural stability	l-cm radius
Maximum Baseline	10 m
Instrument hires with Cabling	1240 kg
Instrument Power	721 W average
Instrument Data Rate	77.8 kbps peak rate
Total Radiation Dose	40 krads (@ 100 mil Al)

The flight system launch configuration inside the launch vehicle fairing is shown in Figure 3. The flight system on orbit configuration is shown in Figure 1.

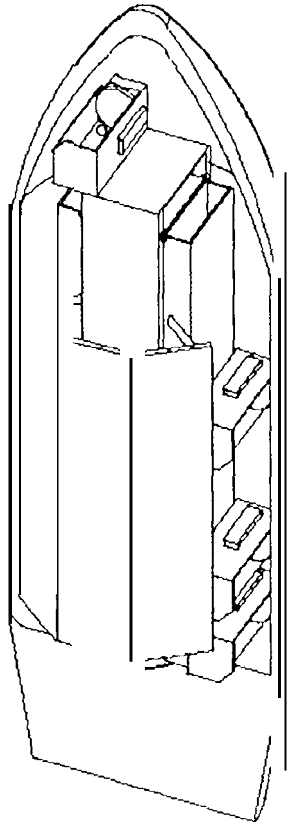


Figure 3 S1 M Launch Configuration

Structure

The central structural element is 5-m long with a 1 m^2 rectangular cross-sect ion, It contains the instrument's beam combiners and most of the engineering electronics. Structural simplicity is emphasized. Three fixed solar array panels are mounted on onc side. An alternate design with articulated solar panels is in development. Two S-m long siderostat arms and a 6-m metrology arm arc attached by means of hinges and deployment struts to the upper edges of the bus.

Structural elements are fabricated from graphite epoxy composite to provide stiffness and minimum thermal deflection. Large scale structures constructed using this approach have demonstrated sub-centimeter thermal distortion/stability on orbit. The closed loop optical systems which are used to compensate for the thermal structural movement have more than adequate amplitude and frequency response capability for compensation

The deployment components used on the flight system draw upon hardware developed in the NASA and military communities, The components for performing the necessary deployments arc within the state of the art

The deployment and latching mechanisms provide sub-micron level stability. The deployment component selection criteria uses existing flight proven designs and components. All joints arc preloaded to eliminate joint backlash. The performance of the deployment components arc validated by ground test at the module level.

The metrology boom assembly is an internally preloaded (zero backlash) AEC-ABLE ADAM Mast A 60-m long ADAM Mast is to be used on the Space Radar Topographic Mapping (SRTM) mission The ADAM Mast is a derivative of ABLE's FAST Mast which will be flown as part oft he Space Station solar array assembly. The flight system uses a scaled down version of the mast used for these two applications. The ADAM Mast is preferable to the FAST Mast because the part and joint count is lower, and the ADAM Mast is athermalized. The ADAM mast is readily scaled to the 100-m length range desired for ExNPS.

The two siderostat booms arc fold out arms that lock into place. JPL has flown or will fly a number of foldout booms, including the NSCAT antennas. the TOPEX GPS boom, and Voyager RTG boom The foldout booms used arc driven by dwrl-drive actuators J PL has a large body of successful experience in the development and use of the very reliable space qualified dual-drive actuators.

All deploy ment assemblies arc qualified to verify deployment functionality and accuracy using gravity off-loading techniques. The siderostat foldout booms arc tested on an air bearing table. The metrology boom is tested vertically, with a gravity off-load device similar to an overhead crane.

Telecommunications

Both uplink and downlink are at X-Band frequency. The downlink bit rate is 20 Mbps. The major telecommunication hardware components are: 4 Low Gain (patch) Antennas (LGA) with a gain of 6 dB each providing 4π steradian coverage, redundant Cincinnati Electronics (CE) X-Band transmitters with 3-W RF internal power amplifiers, and a redundant Small Deep Space Transponder (SDST) to provide for uplink and downlink. Three Waveguide Transfer Switches (WTS) and 4 hybrids configure the LGAs such that each antenna can receive the commanding signal as well as transmit the telemetry.

The downlink data is coded using a rate 1/2, constraint length 7 convolutional code concatenated with Reed Solomon 223/255 code for error correction, The coding provides a Bit Error Rate (BER) of 10^{-6} for a required bit energy to noise density ratio of about 2.5 dB. The telemetry link has a margin greater than 4 dB.

Attitude Control

The spacecraft attitude determination capability is provided by a fine sun sensor, New Millennium technology star tracker, magnetometer, GPS "receiver on a chip" capable of performing attitude determination (GPS ADS), and a fiber optic inertial reference unit (IRU). All sensors are redundant.

The sun sensors and GPS ADS receiver provide coarse attitude information as well as position, velocity, acceleration, and time for the spacecraft. This information is transferred to the star tracker for fine absolute pointing information for attitude determination, The magnetometer is used for magnetic field detection to control the magnetic torquers. The IRU provides angular spacecraft rate information.

Attitude control capability is provided by four reaction wheels isolated from the structure by an active hexapod vibration isolation assembly. The wheels are offloaded by magnetic torquers. Large reaction wheels (Hubble design) allow the spacecraft to rotate 90 degrees in 5 minutes. All actuators are redundant

Power

Sotar energy is converted to electrical power using GaAs cell technology (8-cm² cells) in an array of 14.37 m² combined area. Solar array power of 1912 W in direct sunlight is delivered using a direct energy transfer system incorporating a shunt limiter, secondary battery and charger, and load switching at a nominal 28 Vdc. A capacitive discharge pyro system is included to deploy the booms. The secondary battery of 40 Ah Ni - H_2 (IPV) cells is sized to deliver 200 W for 4 hours which supports both launch and eclipse power requirements. The power system is redundant.

Command and Data Handling

The spacecraft controller provides centralized command and data handling functions required by the spacecraft from launch through end of mission These functions include command processing, telemetry data processing, mass storage. attitude control computational support, and executive control.

The spacecraft controller decodes, validates, buffers and issues ground commands received from the telecommunications subsystem It also generates and issues validated control commands resulting from parametric computations performed in support of attitude control functions during orbital operations.

The spacecraft controller continuously acquires 2 kbps of engineering data in both analog and digital form, which is digitized, packetized and buffered. The controller also receives, processes, buffers, packetizes, and compresses (2:1 lossless) the 77.8 kbps digitized payload data. The controller merges all spacecraft engineering and paytoad data packets into a single telemetry data stream This packetized telemetry data is Reed-Solon~on encoded, buffered and placed into mass storage for later transmittal to the ground.

Data is stored on board at 6.9 Gb/day, on a 64 Gb redundant DRAM storage device. A Transparent Asynchronous Xmitter-Receiver Interface (TAXI) (available as a radiation hardened two-chip set) is used to provide high speed transfer (5- 100 Mbps) from the mass storage memory to the tele-communications subsystem. The data is downlinked in less than 12 minutes every 4 days at 20 Mbps, with large margins.

An architecture similar to that of the Mars Pathfinder Attitude and Information Management Subsystem is used This features an advanced Reduced Instruction Set Chip RS6000 Central Processing Unit capable of high speed computations and control functions combined with a VME backplane There are 256 Kbytes of EE PROM (boot PROM). The VME backplane provides standardization for all interfaces for both flight and ground (test) equipment The spacecraft controller acts as bus controller at all times. with each subsystem interfacing to the bus through a standard bus interface unit (BIU). The high density memory board provides Direct Memory Accessing (DMA) capability. and double error detection and single correction for 10 Gbits of DRAM per board

Propulsion

Since the flight system is injected into a sufficiently accurate and stable orbit to meet all science requirements well beyond the mission lifetime without spacecraft propulsive maneuvers, no propulsion system is required

Thermal

The thermal control subsystem maintains the structure temperature within required temperature and thermal gradient limits to maintain the structural alignment of the optical elements, as well as meet electronics and instrument flight allowable temperatures.

The design uscs flight proven elements, including multi layer insulation enclosing the entire structure to minimize gradients leading to thermal distortion, thermal louvers, electric heaters/thermostats, thermal surfaces and radiators, and thermal conduction control.

The structure is isolated from the active elements (siderostat, beam launchers, etc.) with multilayer insulation and thermal isolators. Each of the instrument thermally-critical elements maintains its *own* thermal control. The instrument optics are nominally maintained at 20”C and the instrument detector is maintained at -90°C. Active heaters and electronics are used as needed. None of the thermal cent rol elements require additional development.

System Margins/Robustness /Risk

The flight system mass is shown in Table 5. The flight system power is shown in Table 6.

Large margins for mass, power, memory, and tolerance to the environment arc provided in the design. Long life designs with no consumables further enhance the system robustness. All engineering subsystems arc fully redundant. Hardware used is expected to be developed by commitment deadlines, and an acceptable backup ensures the ability of the flight system development to meet schedule constraints. All the above reduce cost risk. The result is a flight system design that is robust, with minimum development and flight risk.

Table 5 Flight System Mass Estimates

	kg
Engineering	
Structure	65
Telecommunications	18
Attitude and Isolation Control	251
Power and Pyro	89
Command and Data Handling	32
Propulsion	- Q
Total Engineering	455
Science Payload	
Starlight Subsystem	676
Metrology Subsystem	69
Precision Structure, Thermal, and Cabling	400
Realtime Control Subsystem	95
Total Science	1240
L/V Adapter	112
Total Flight System (CBE)	1807
L/V Capability	3000
Margin	66”0

Table 6 Flight System Power Estimates

	Watts (avg.)		
Engineering	Science	D/L	Sci & Batt Chg
Structure	0	(J	(J
Telecommunications	12	46	12
Attitude Control	132	132	132
Power	80	80	489
Command and Data Handling	23	23	23
Propulsion	0	0	0
Total Engineering	247	281	656
Science Payload			
Starlight Subsystem	281	281	281
Metrology Subsystem	200	200	200
Precision Structure Subsystem*	69	69	69
Realtime Control Subsystem	171	171	171
Total Science Payload	721	721	721
Total Power Required	968	1002	1377
Solar Panel Capability	1912	1912	1912
Margin	98%	91%	39%

• Includes Thermal and Cabling

4. Mission Description

The orbit selected for SIM, shown in Figure 4 is near polar. circular and Sun-synchronous. The altitude is 900 km, the inclination is 99.034°, and the period is 102.9 minutes.

This orbit provides the following significant advantages:

- by synchronizing the orbit to pass over the terminator (a “dawn-dusk” orbit that crosses the equator at 6:00 local time), the flight system receives relatively uniform solar illumination throughout individual orbits and throughout the year
- the radiation environment is significantly more benign than for higher altitude orbits
- the flight system avoids eclipse on at least 265 days per year even under worst-case launch vehicle injection errors and orbit perturbations over five years. The maximum eclipse time is less than 20 minutes per orbit
- a propulsion system is not required to achieve nor maintain the orbit. The absence of a propulsion system eliminates mechanical disturbances induced by fuel slosh. reduces the spacecraft cost and complexity, and removes a potential source of contamination for the optics
- magnetic torque rods can desaturate reaction wheels eliminating the need for a gas system or an elaborate slewing scheme
- the orbit is beneath the GPS constellation at 20,000 km attitude so GPS receivers on the spacecraft easily enable achievement of the required

4 mm/sec velocity knowledge to correct for stellar aberration.

- The 900-km orbit allows SIM to use a smaller launch vehicle

The launch vehicle chosen for SIM is a Delta II 7920 with the 10-ft fairing. This Delta has a payload capability to the desired orbit of 3000 kg. Since a third stage is not required to obtain the desired orbit, the entire fairing volume can be used. This allows the current SIM architecture with a baseline of 10 m.

The key constraints for designing an observational scenario are on the direction in which the nominal viewing axis may point. The siderostats articulate ±2.5° in both azimuth and elevation about this axis. Baffles protect the siderostats from direct heating by the Sun and Earth, satisfying thermal constraints on the siderostat mirrors. Given the geometry of the baffles, it is required that the Sun not be within 50° of the nominal axis and that the limb of the Earth not be within 30°. Based upon these constraints, an example observational scenario has been developed and is shown in Figure 5.

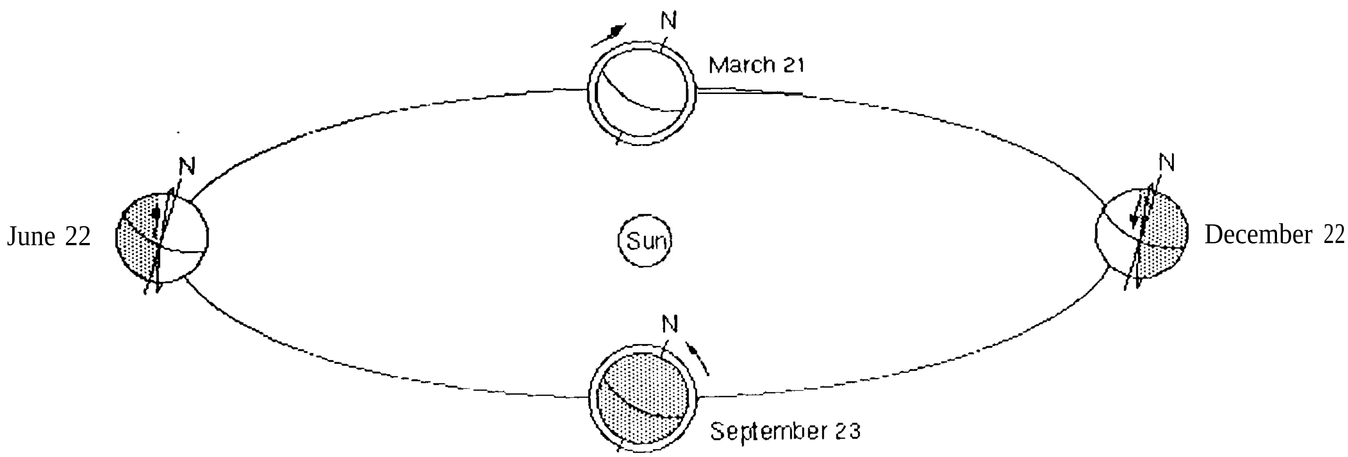
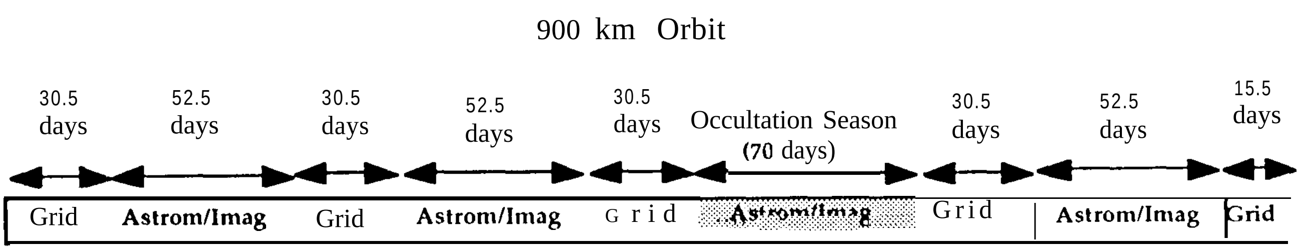


Figure 4 SIM Sun Synchronous Orbit



- Number of Grid Tiles = 5733 — % of Year= 25,6 %
- Number of Astrometric Tiles = 5298 — % of Year = 25.6 %
- Number of Images = 6 — % of Year= 1.9 %

Slewing, Settling, Calibration/Engineering, occultations, South Atlantic Anomaly, Inefficiency = 4s.9 %

Figure S One Year Observational Scenario

5. Mission Operations System

The SIM Mission Operations system makes maximum usc of existing multimission facilities reducing the cost and risk associated with developing new and unique systems. Typical of such facilities are the Alaska SAR Facility (ASF) Tracking Antenna, JPL's Multimission Ground Data System (MGDS), JPL's Multimission Command System and JPL's Multimission Navigation Facility as shown in Figure 6. The reduction of cost and risk by automation of processing, use of proven off-the-shclfor locally developed software and hardware, and ease-of-useby the end users arc the design drivers at each stage in the development of mission operations for SIM.

Command and Telemetry

A possible tracking station is the ASF'S 11 m antenna at Poker Flats, Alaska. This station provides X-band uplink and downlink to the spacecraft. Required uplink commands are passed from JPL's Multimission Command System to the Alaska SAR Facility's control subsystem as needed. Downlink telemetry are shipped with tracking information back to JPL's MGDS. Downlink occurs on a daily basis for the first 30 days. After that, downlink occurs during an approximately 12-minute window once every 4 days. There is a significant cost and complexity advantage to downlinking only once every -i days Scheduling the antenna is less difficult and the need for operations personnel is reduced The link provides a data rate of 20 megabits/scc yielding roughly 14.7 Gb of science and engineering data at a nominal lossless compression ratio of 2:1 delivered to JPL.

The existing MGDS Command System for uplink commanding will bc adapted to send commands to the spaccc ra ft.

Navigation and Ground Data Processing

JPL's Multimission Navigation Facility (NAV) receives tracking data to monitor the spacecraft's orbit and provides orbit predictions which in turn feed back into the uplink command sequencing. Navigation data is stored in the Project Data Base (PDB) in the JPL MGDS. All software modules necessary to perform these operations have been developed and arc maintained by the NAV staff.

JPL's MGDS captures, routes and stages the telemetry and ground monitor data received from the Alaska SAR Facility. All data is managed and archived on the various subsystems within the MGDS and is readily available to the project and

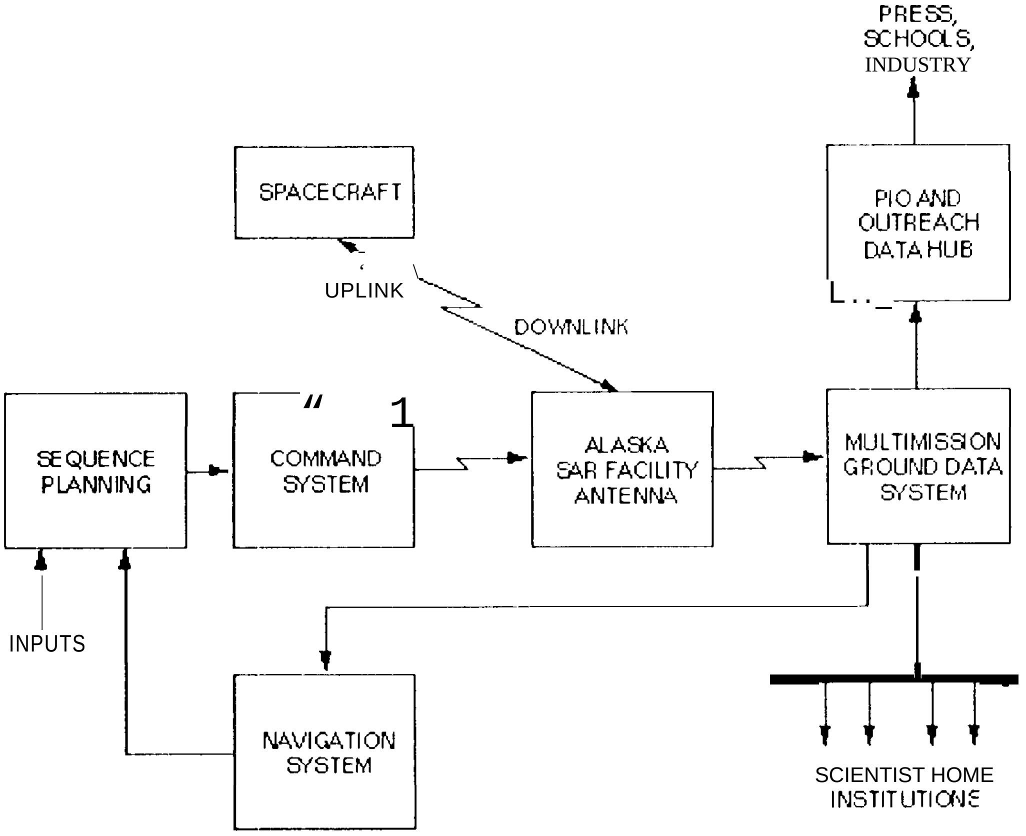


Figure 6 SIM Mission Operations System

science staff. The principal archive of engineering, navigation and ancillary operations data is the PDB but the science data and essential ancillary information are catalogued and archived during mission operations in the Multimission Instrument Processing System (MIPS), which maintains a distributed secure link with the science community. Instrument health and monitoring and science data management software are based on project specific adaptations of current and currently-planned software for such capabilities within the MGDS and JPL's Flight System Testbed. JPL provides a data hub for products used in the SIM educational, community or industry outreach programs.

Home Institution Science Processing Systems

Science processing is performed on workstations at the scientist's home institution. Scientists use commercial off-the-shelf analysis packages or locally-written software for their analyses. Science data catalogued and archived at JPL's MIPS facility is available 24-hours per day via a network along with necessary ancillary information for browsing and data transfer. The science team provides direction as to the distribution and availability of all data. Archival data formats conform to standards set by the science team. Delivery of science products produced by home institutions to any archive facility is at the discretion of the science team.

6. Project Status

The SIM Project has completed the pre-Phase A activities and has entered into Phase A. Figure 7 presents the SIM project schedule showing the key activities leading to the launch of the flight system in June 2005. The SIM design incorporates demonstrated technology that is currently producing valuable science data in ground based interferometer operations. An extensive technology program will continue during Phases A and B that will influence the final SIM design During Phase A, an Industrial Partner will be selected to build the spacecraft.

Additionat information about the SIM Project can be obtained from the SIM Home Page at the address h(tp://hucy/framctcst/Docs/framc 1.html.

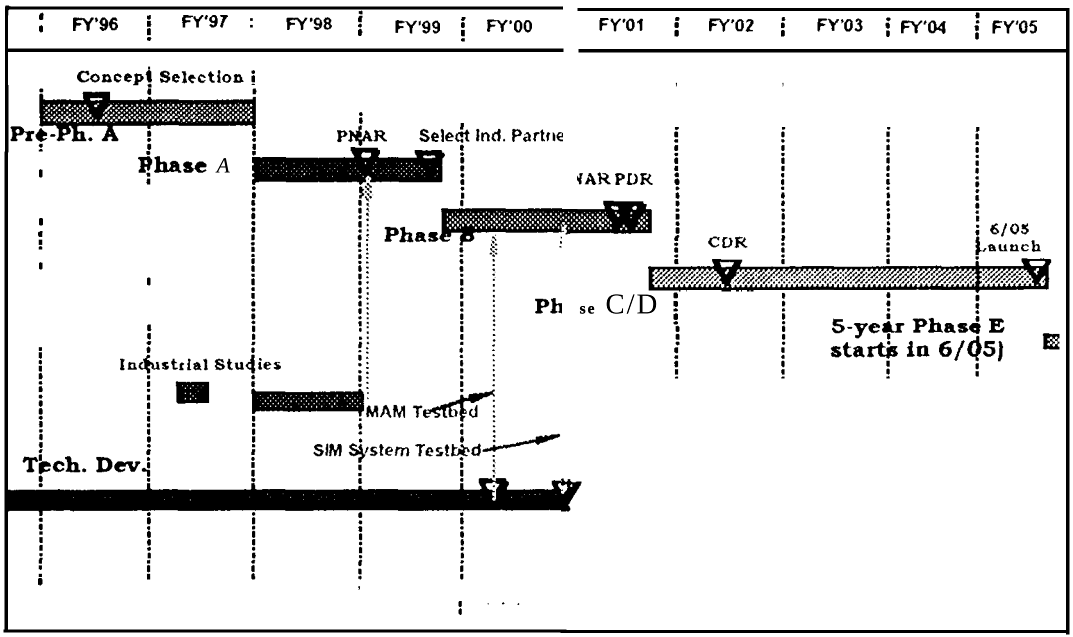


Figure 7 SIM Project Schedule

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Dr. Dallas joined JPL as an engineer in June of 19.59. Since that time, he has been involved in research associated with the motion of artificial and natural celestial bodies. He has written many articles and reports on this subject. Current[y, Dr. Dallas is the Mission System Manager for the SIM Project. In this capacity, he has the responsibility of managing the mission design and mission operations development activities for the Project.

Prior to this assignment, Dr. Dallas was the Mission Manager for the Mars Global Surveyor Project. in this capacity, he had the responsibility of managing the mission design and mission operations development activities for the Project.

Prior to this assignment, Dr. Dallas was the Mission Manager for the Mars Observer Project. In this capacity, he had the responsibility of managing the mission design and mission operations activities including the Science Operations Teams, the Spacecraft Team, the Navigation Team and the Sequence Team for the Project.

Prior to this assignment, Dr. Dallas was the Science and Mission Design Manager for the highly successful Magellan Project. In this capacity, he had the responsibility of managing the science planning activities, the Navigation Development Team, and the Mission Design Team for the Project.